Jet Propulsion Laboratory
California Institute of Technology

Low Thrust Trajectory Bacon Plots for Mars Mission Design

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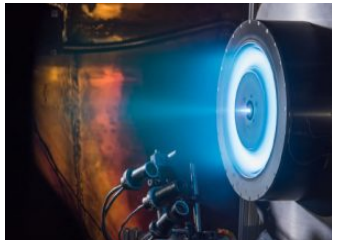
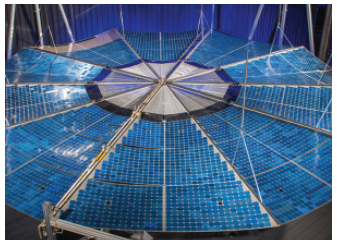
SEP for Interplanetary Missions

- Six missions using Solar Electric Propulsion flown:
  - Deep Space 1 (1998) – comet
  - Hayabusa (2003) – asteroid
  - SMART-1 (2003) – moon
  - Dawn (2007) – Vesta and Ceres
  - Hayabusa 2 (2014) – asteroid
  - Bepi-Colombo (2018) – Mercury

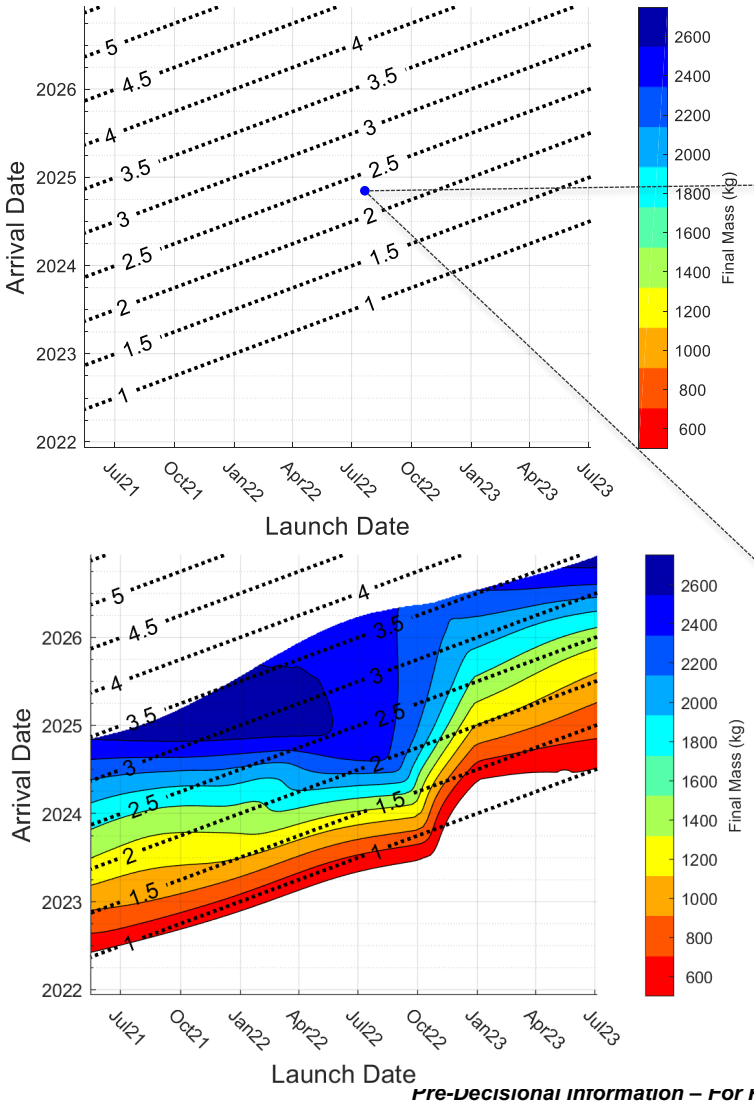
- Lots of technology advancement over past decade
  - High-power, commercial Hall and ion thrusters
    - SPT-140, NEXT, XR-5, XIPS
  - Lightweight flexible solar arrays
    - UltraFlex and MegaFlex, ROSA

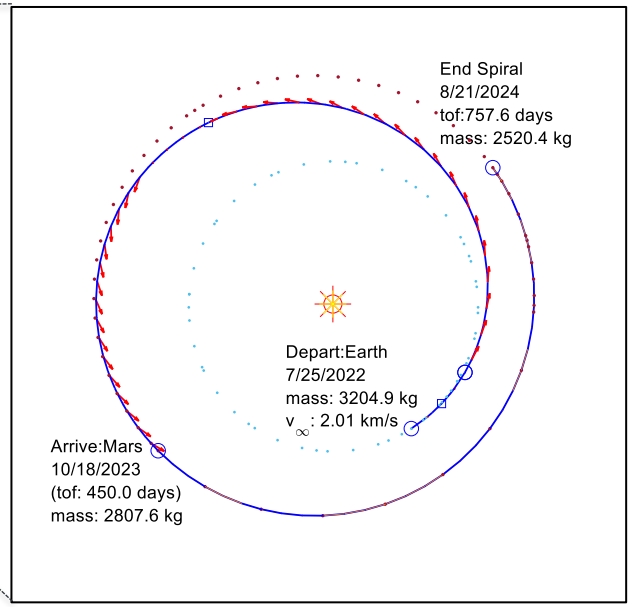




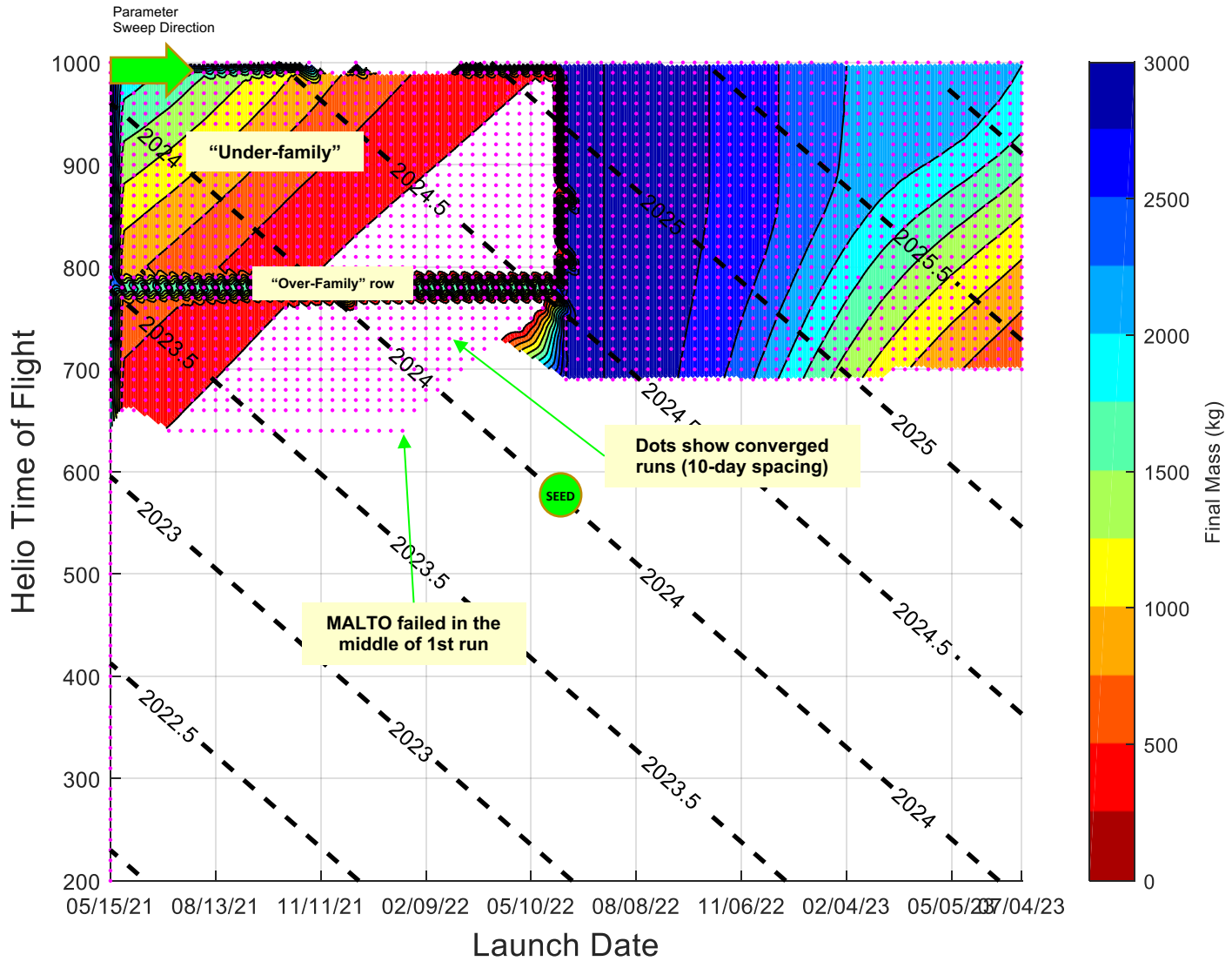
Sampling an Unknown Space

Where do you start mission design for SEP to Mars?





Makin' Bacon Plots



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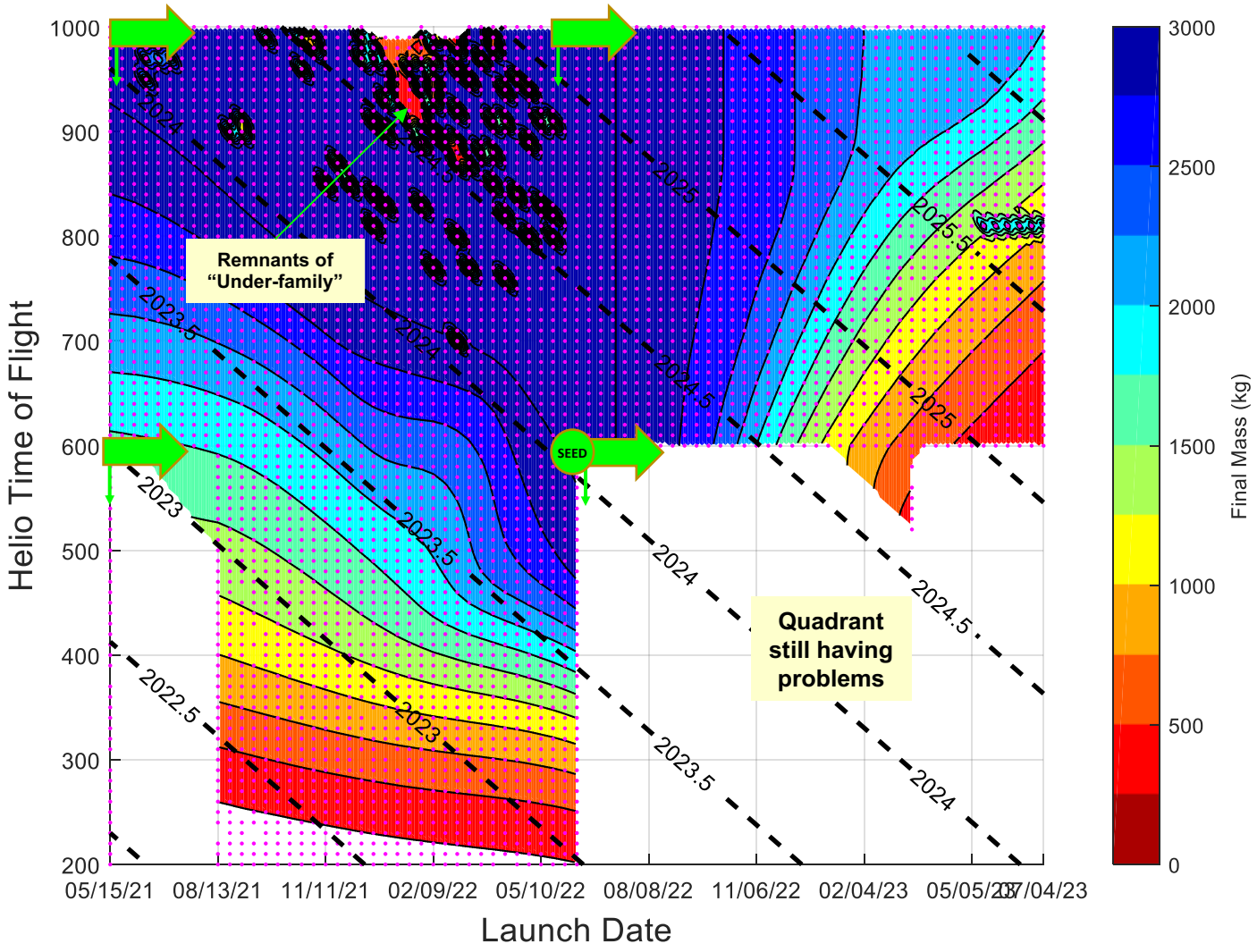

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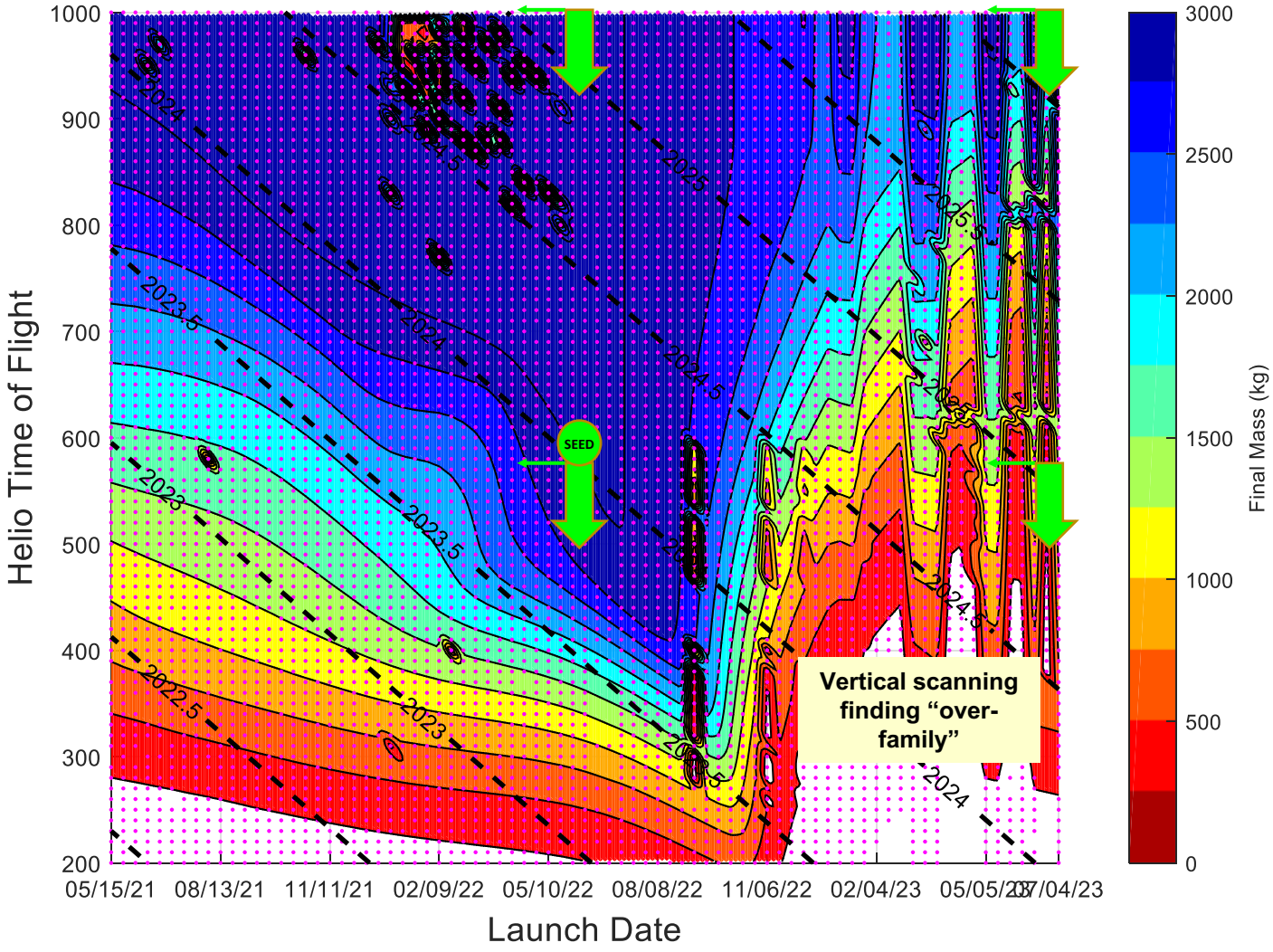

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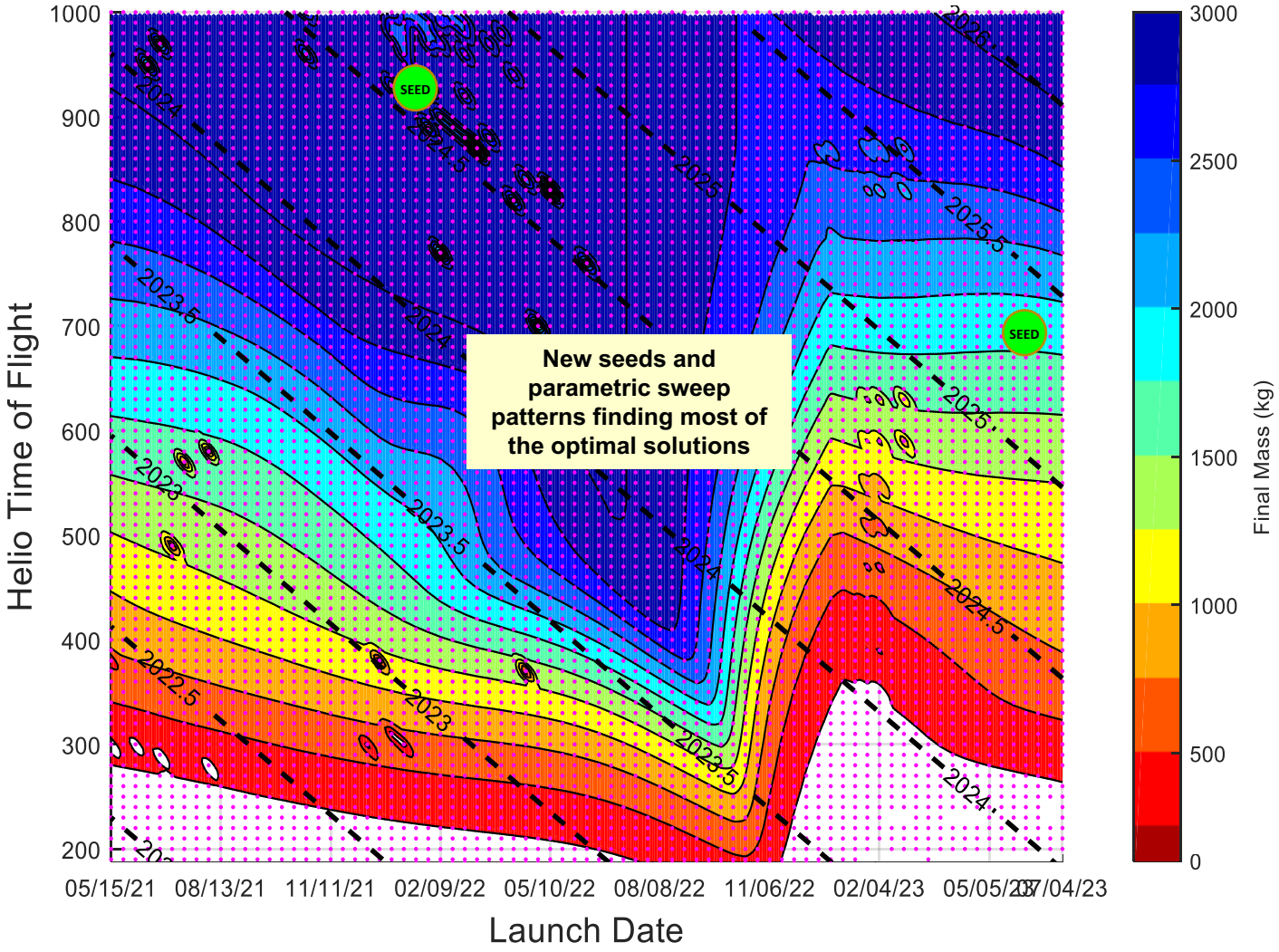
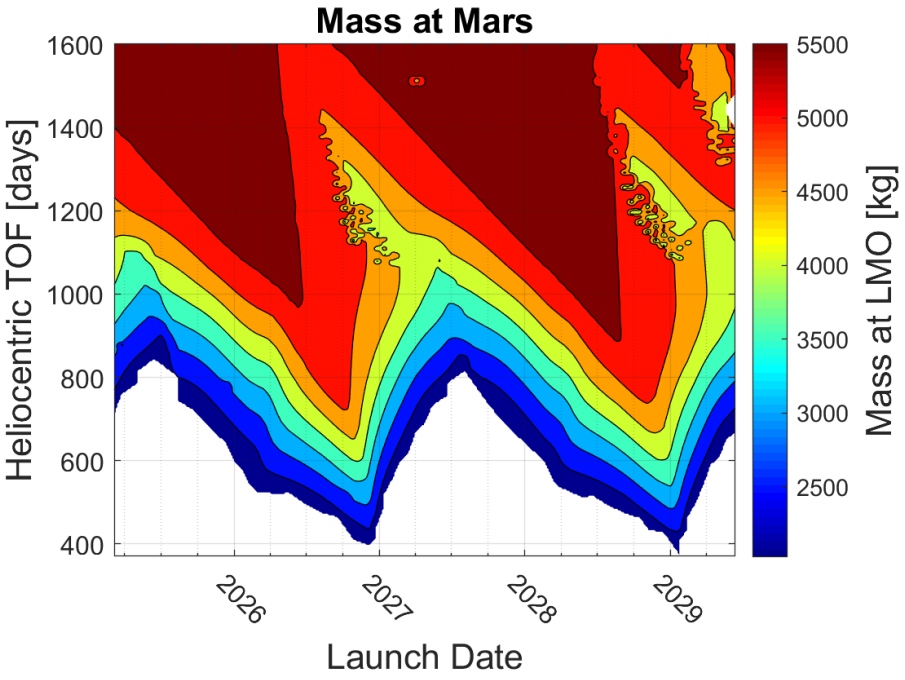
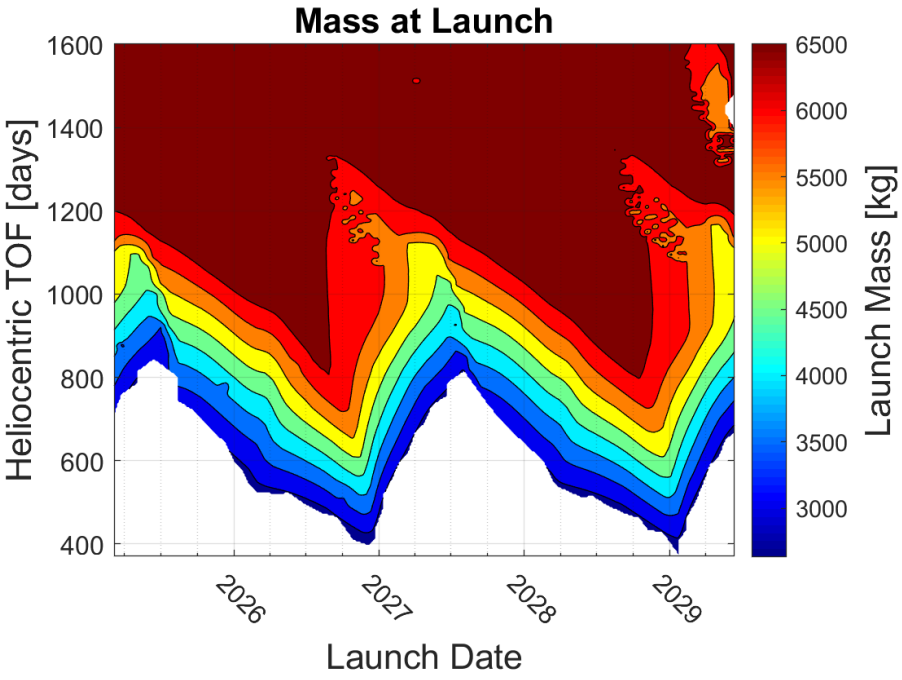


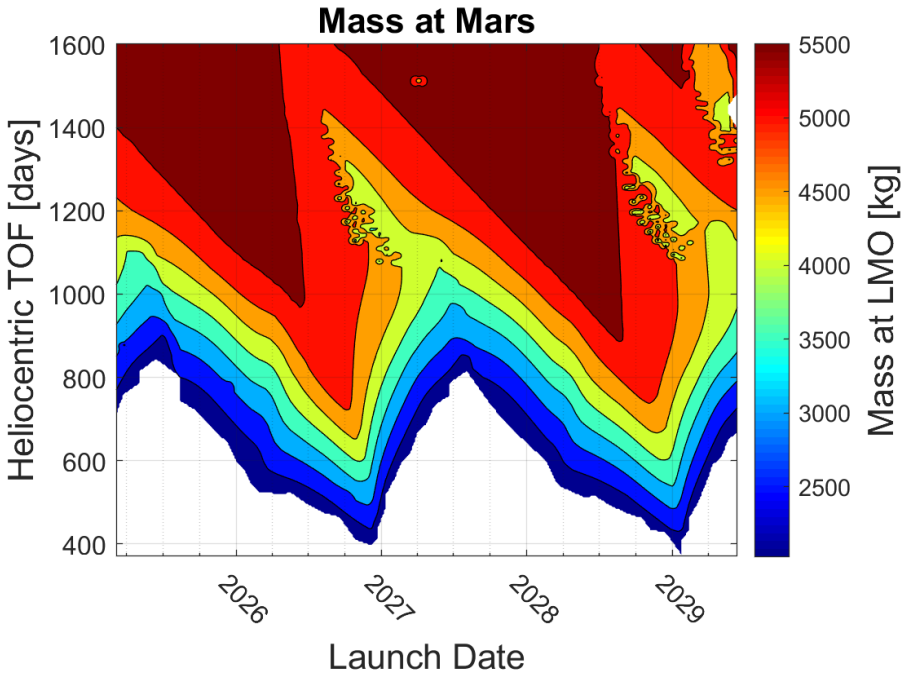
Contours of Other Parameters

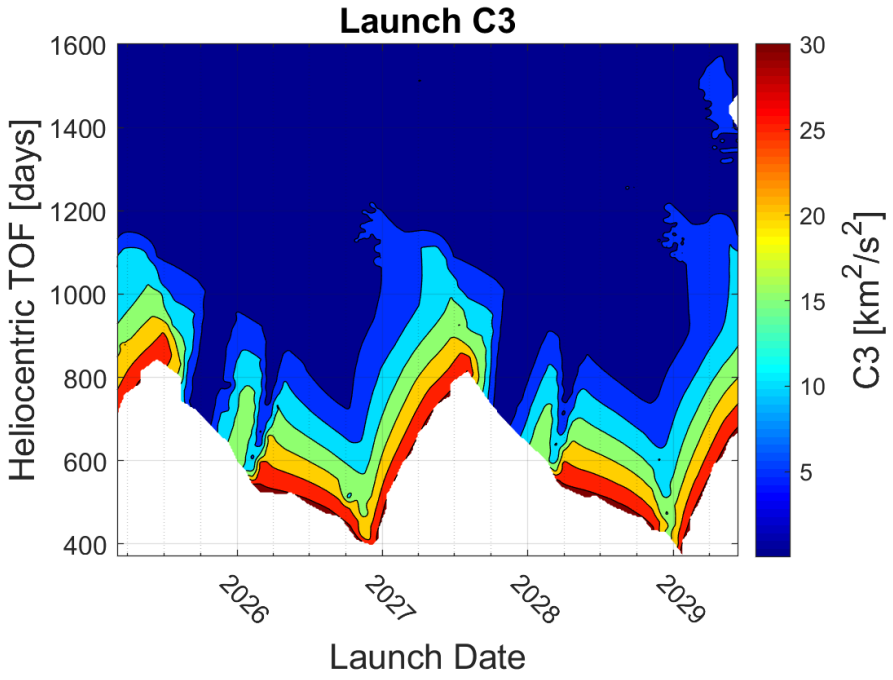




- Each trajectory point has a range of associated parameters that can be plotted
- (Left Plot) Standard bacon plot with final mass
- (Right Plot) Optimized starting mass

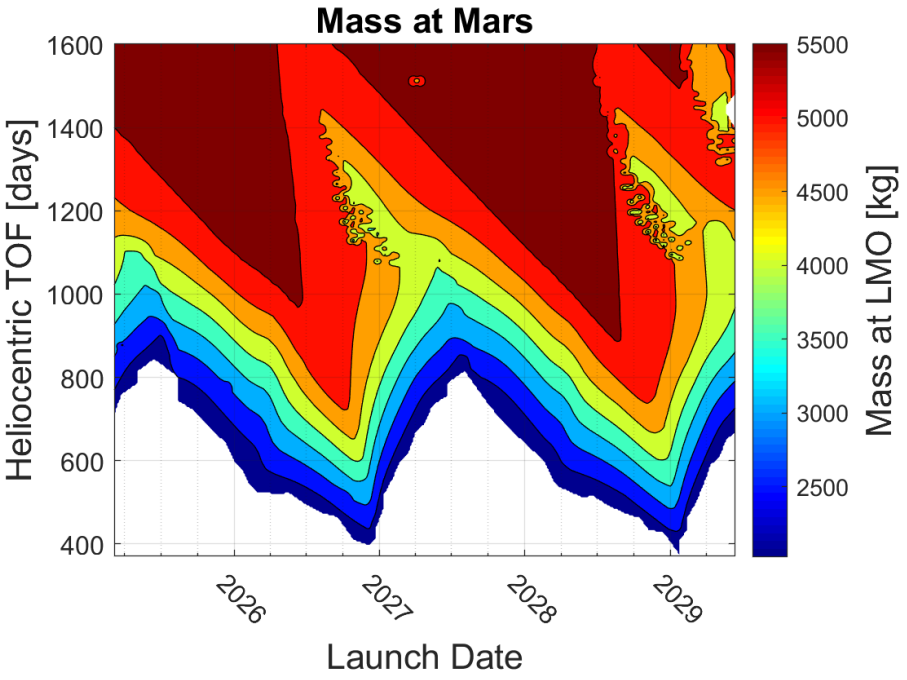
Contours of Other Parameters

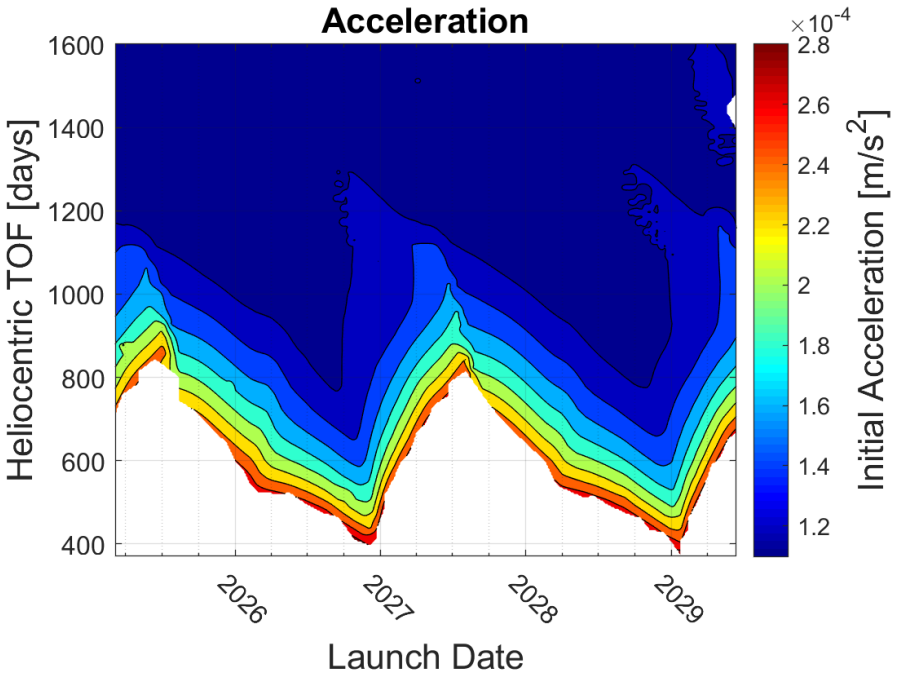




- Higher launch masses are achieved by being able to launch to lower C3 for given launch vehicle
- Higher C3's are needed to reduce trip times, subject to planetary alignments

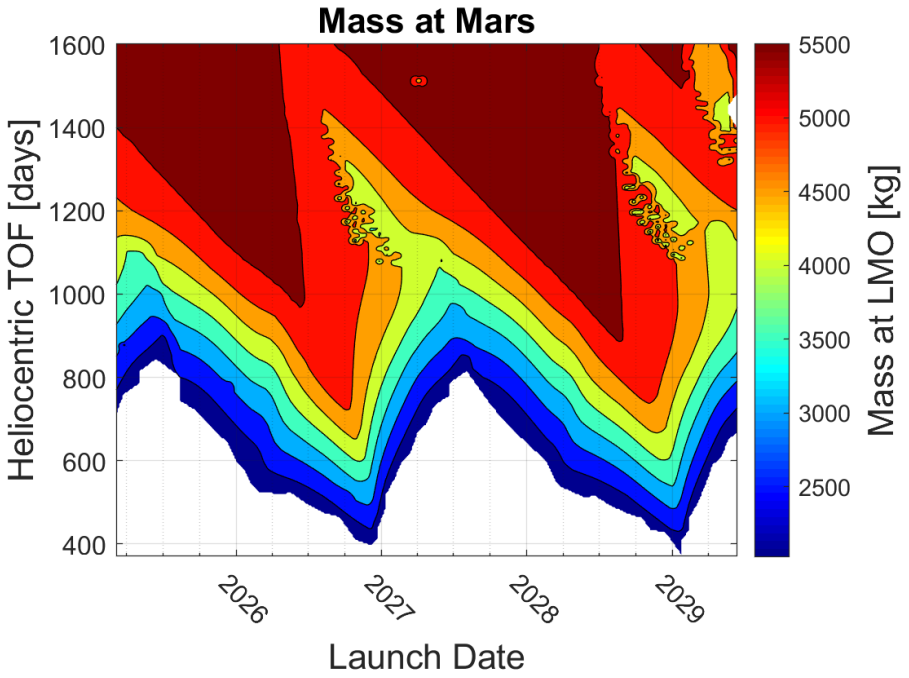
Contours of Other Parameters

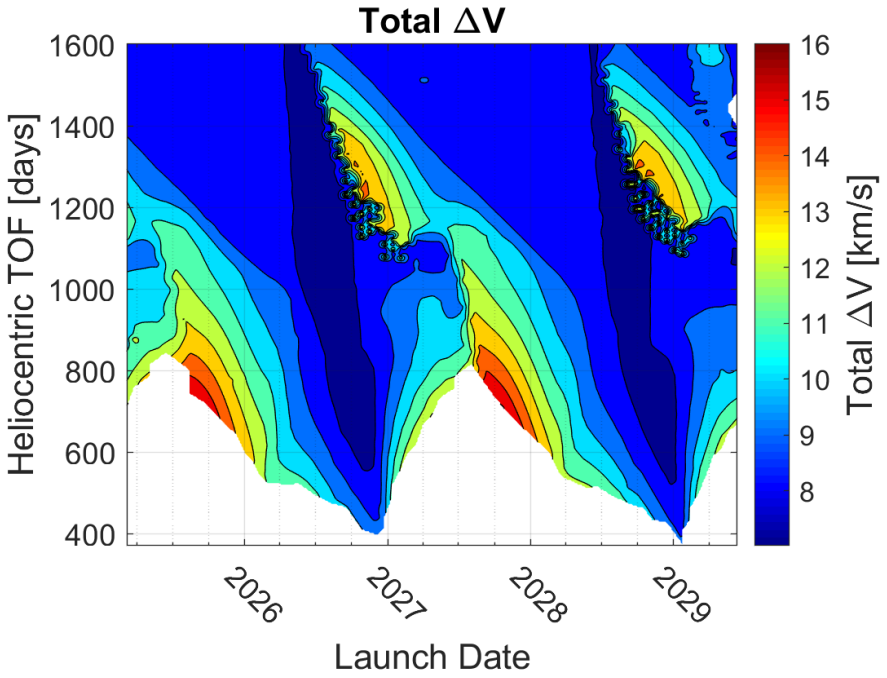




- Since power and thruster are fixed, acceleration at Earth is a direct function of launch mass
- Initial accelerations are typically 0.15 – 0.3 mm/s^2

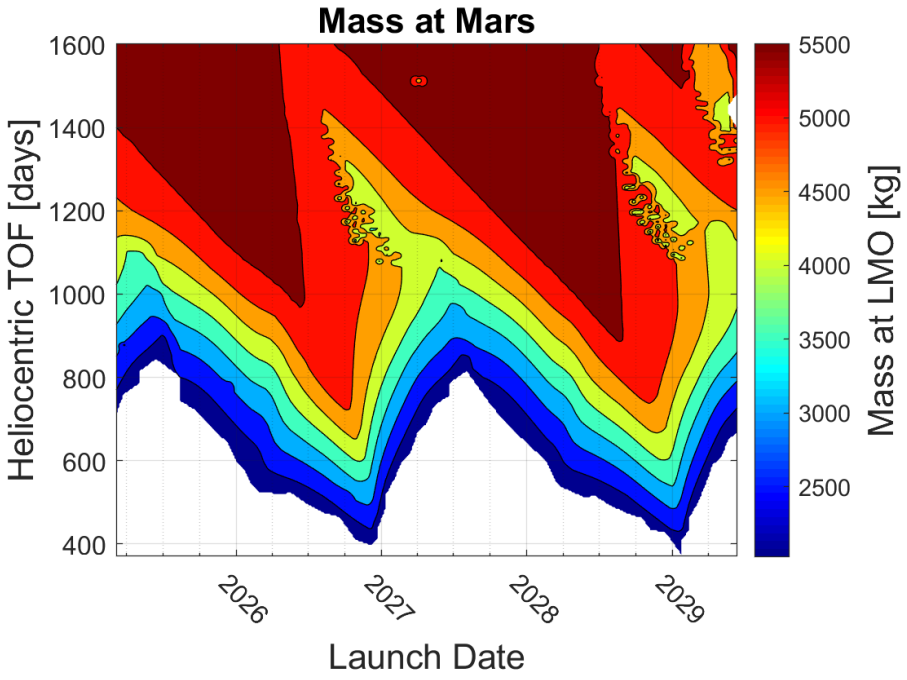
Contours of Other Parameters

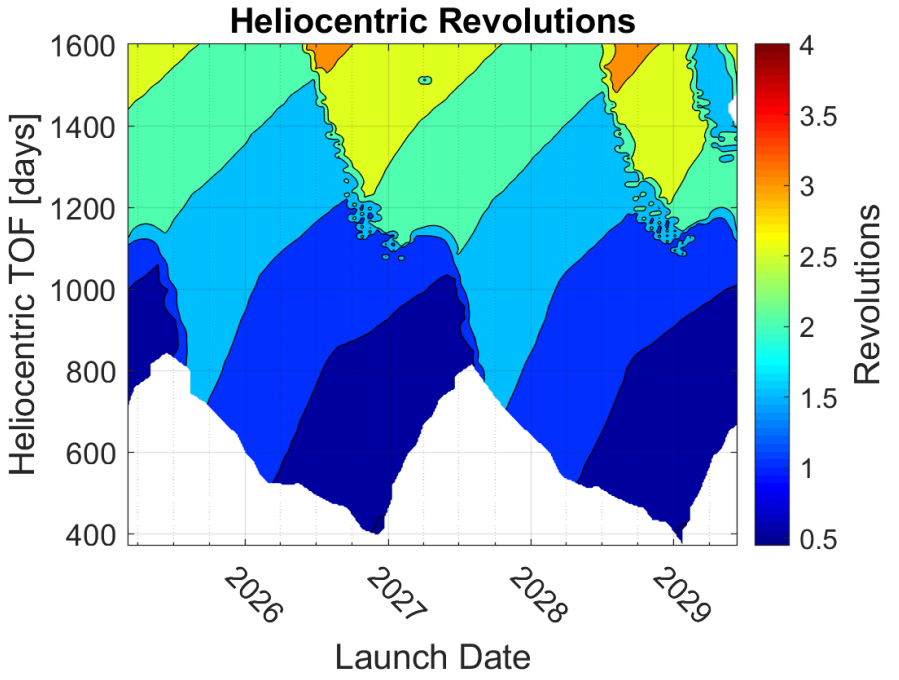




- ΔV is minimized during optimal alignment every 26 months, corresponding to ballistic transfers
- Minimum ΔV here is 7 km/s, which in the limit goes towards the Hohmann limit of 5.7 km/s

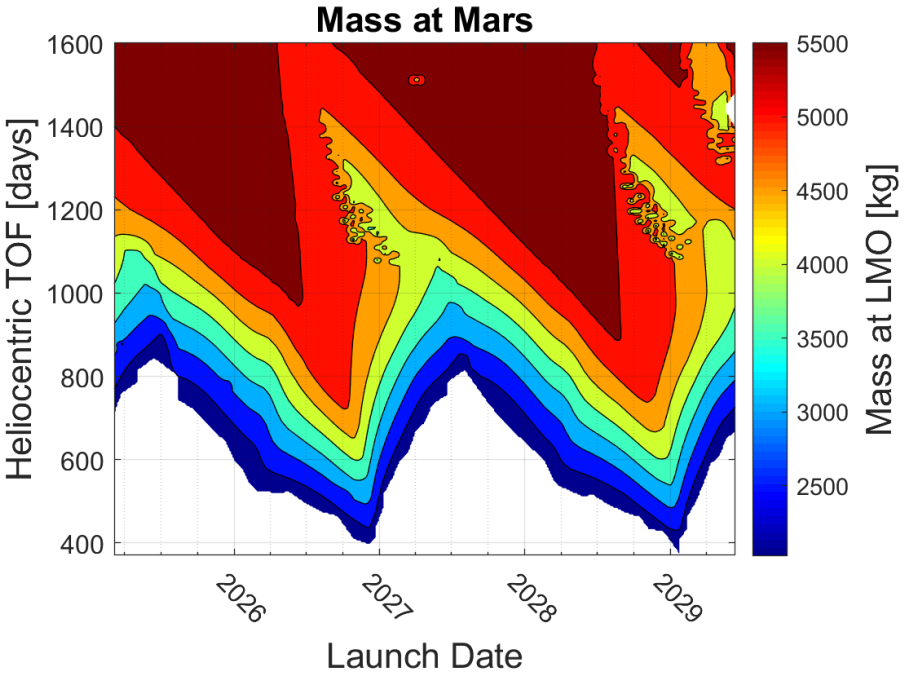
Contours of Other Parameters

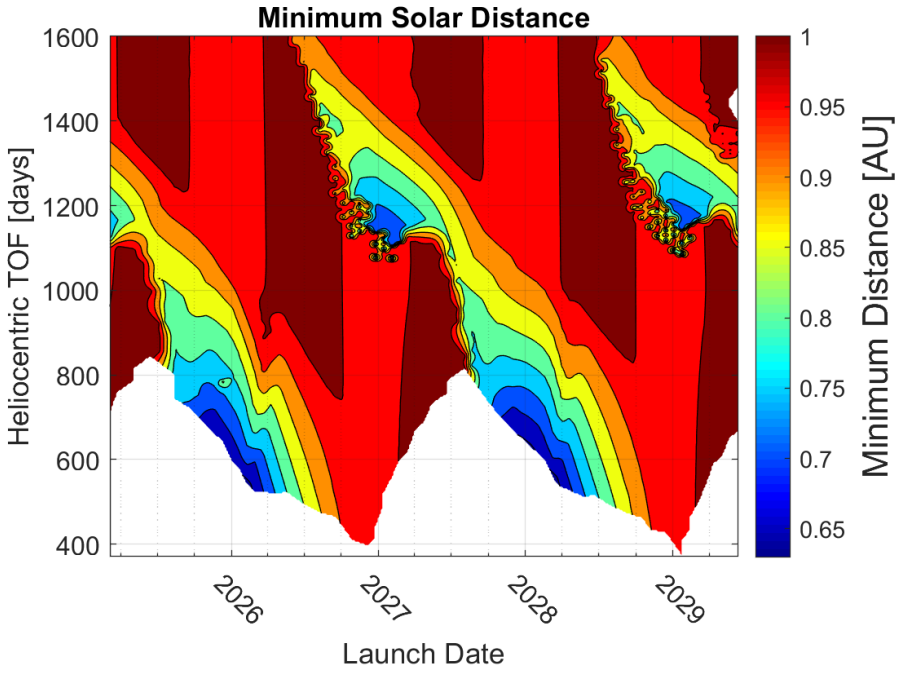




- Solar revolutions have a discontinuity boundary where it becomes more optimal to use n+1 revolutions
- Often cause the most difficultly for optimizers to find true “over family” vs. “under family”

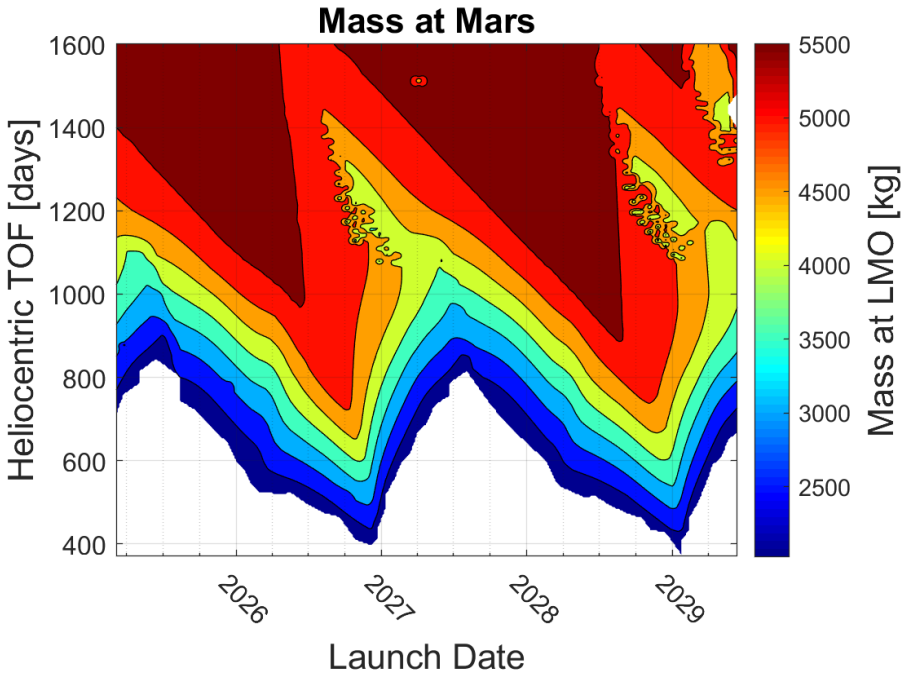
Contours of Other Parameters

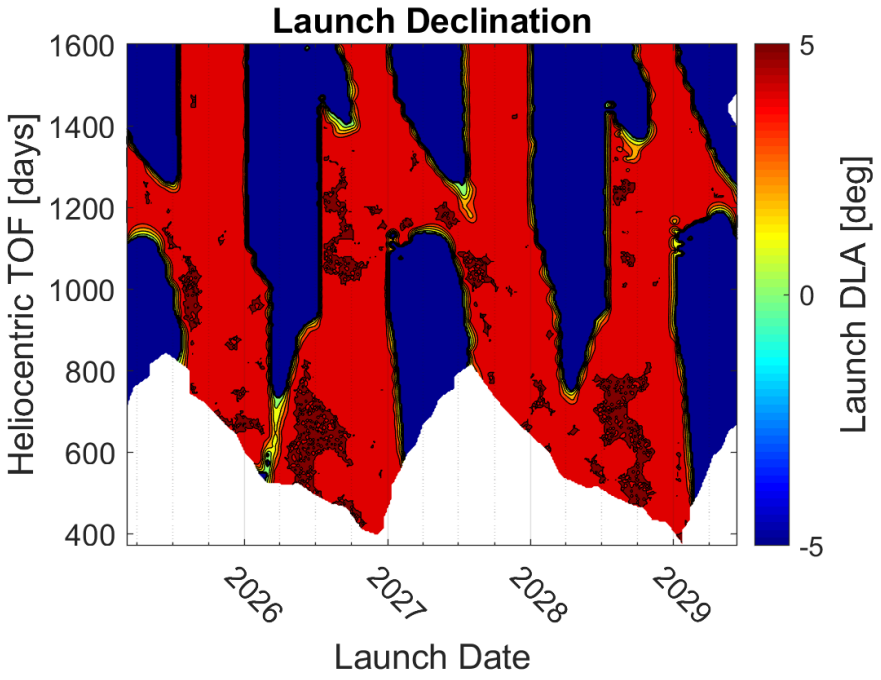




- For fast transfers outside of the natural geometries the trajectories may go as close as Venus's orbit
- Typically correspond to the highest ΔV's

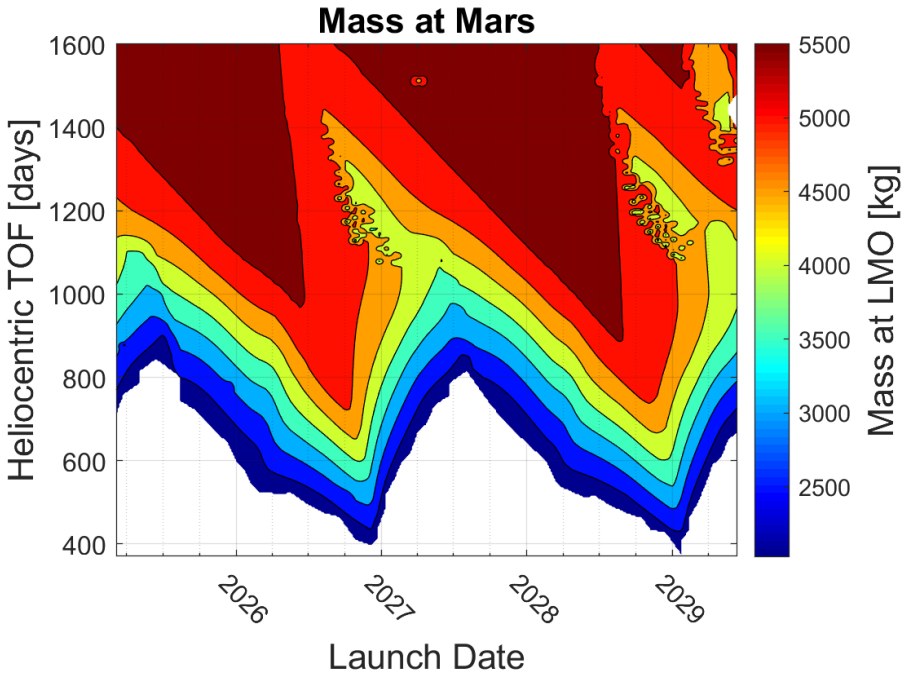
Contours of Other Parameters

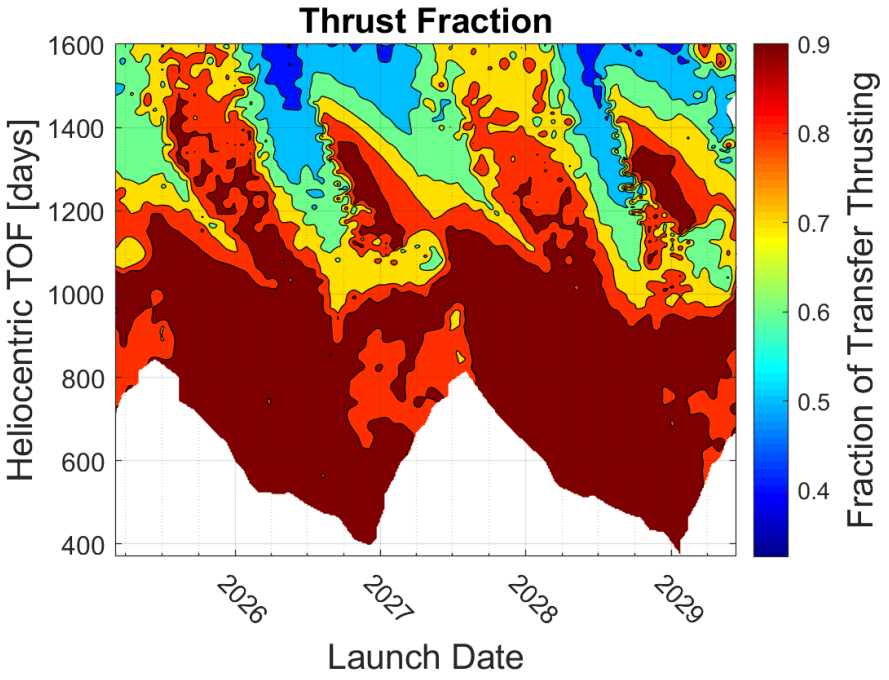




- Launch declination alternates on roughly an annual cycle between N and S, due to Mars's solar inclination
- This example was constrained to +/- 5 degrees
- Typically SEP DLA's are lower than ballistic counterparts

Contours of Other Parameters





- For faster transfers virtually the whole time is spent thrusting
- Thrust fraction is capped here at 90% due to duty cycle
- Longer transfers have optimized coasts

Using Bacon Plots in Preliminary Mars Mission Design

- Sweeping multiple SEP trajectory inputs and plotting the output contours can help answer questions like:
  - What is the latest/earliest we can depart/arrive?
  - How long is the launch period?
  - What does it cost to constrain some date or duration?
  - What happens if dates slip?
- Bacon plots aid in general intuition and awareness of how parameters vary in SEP mission design
- Bacon plot data created for various power levels and thrusters can be used in conjunction with spacecraft design tools to find optimal mission architectures